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SIMULATOR STUDIES OF SPACE AND LUNAR LANDING TECHNIQUES

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SIMULATOR STUDIES OF SPACE AND LUNAR LANDING TECHNIQUES

By Byron M. Jaquet*
NASA Langley Research Center

INTRODUCTION

Simulators and flight trainers have been used extensively in the aeronautical industry over the past 20 years (ref. 1). Actually, the first flight simulators appeared on the scene shortly after the first flight of the Wright Brothers (ref. 2). As each advance in flight occurred, the requirements for flight trainers have increased. Now that man has started the exploration of space the need for space flight trainers and simulation devices is even greater. Simulators and flight trainers are used to develop techniques for task performance, to determine the proper location of controls and displays for the astronaut, to determine what and how information should be displayed for efficient man-machine integration, and to determine how well man can perform the task under normal and emergency operations. One of the most important areas is that of emergency operation where the astronauts must be thoroughly familiar with all phases of system operation since in many situations only they will be able to help themselves. The purpose of this lecture is to review some of the simulator studies pertinent to space flight and lunar operations. This review will be limited to studies involving man as the primary source of command. Only a few unclassified studies have been included herein. It should be noted that many studies have been performed by members of the Aerospace Industry. (Reference 3 contains a list of many unclassified studies.) This review is an extension of one presented by Mr. W. H. Phillips of the Langley Research Center for the American Society of Mechanical Engineers in Los Angeles, California, March 1963 (ref. 4).

AREAS OF SIMULATION

Task areas which have received some attention through simulator studies involving manual control are indicated in figure 1 and include: earth launch, rendezvous, orbital assembly, docking, lunar orbit establishment, lunar landing, lunar self-locomotion, lunar launch, and entry into the earth's atmosphere and landing. Some space missions may include all task areas and others may include only a few.

It will not be possible today to discuss all of these studies, or even just a few in great detail; however, references and a bibliography are included for details. Rendezvous, docking, lunar landing, and lunar self-locomotion will be discussed. In a later section some newer research facilities will be discussed.

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*Aerospace technologist, Astromechanics Branch, Space Machanics Division.

RESULTS OF SIMULATOR STUDIES

Rendezvous

Many space missions will have inherent rendezvous requirements such as resupply, rescue, orbital assembly, orbital transfer, and satellite inspection. Therefore, a number of studies of rendezvous techniques have been made. In one of these studies (ref. 5) a star background was projected on the inside of an inflatable planetarium. The target space station was represented by a flashing light, the position of which was controlled by a servodriven mirror in response to signals from the analog computer. The pilot was provided with instruments displaying simulated data which would be obtained from onboard radar and from his own attitude references. Because typical rendezvous missions involved relatively long time periods (greater than 10 minutes) the pilot had adequate time to make decisions and perform tasks involved in controlling his vehicle. The pilot acquired the target by observing the flashing light. Then, noting the apparent target motion with respect to the star background, he applied thrust in the desired direction to arrest the motion of the target with respect to the star background. Thus, the target vehicle was approaching on a constant bearing course. Finally, following a scheduled braking maneuver of range rate as a function of range, and simultaneously maintaining the constant bearing course, the pilot effected the rendezvous. This technique proved easy to learn.

Other rendezvous simulations have been made to determine the effects of radar noise (ref. 6), very low thrust (ref. 7), and eliminating range and range rate information (ref. 8). Even in the latter case, the pilot with the aid of optical sighting devices was able to effect a rendezvous by utilizing a technique to determine range by timing the apparent angular motions of the target during thrusting periods.

Lunar launch and rendezvous have also been investigated in simulation studies. The plan of one such fixed-base two-dimensional study is depicted in figure 2. In the lift-off or boost phase, the pilot visually determined his lift-off time by observing the position of the station (a light spot) against a projected starfield or by determining the station elevation above the lunar horizon with the aid of an etching on the cabin window or some hand-held device. After lift-off the pilot controls his attitude with an acceleration command system while attempting to follow a predetermined pitch program. The pilot monitored altitude and time to see that he remained on or near the nominal trajectory. The pilot commanded main engine cut-off at a particular time in the boost phase depending on the desired coast angle from booster burnout to station altitude (100 miles).

Three different trajectories requiring three different pitch programs and cut-off times were chosen to study the effect of launch trajectory on the launch window for rendezvous; corresponding coast angles from booster burnout to apogee were 24°, 90°, and 180°. The pilot was required to perform each program from memory. Missions were terminated at a relative range of 3 miles with a closing velocity of 10 fps. The ratio of fuel used to fuel required to perform a perfectly executed maneuver is summarized in figure 3 as a function of launch time from the nominal on-time launch of the 24° transfer. From the circle data points it can be seen that there is a margin in launch time of about 2 minutes between the 24° and 90° trajectories and about 4 minutes between 24° and 180° trajectories. The higher fuel consumption data were obtained on the early runs with decreasing amounts of fuel on subsequent runs. Coast times varied from 10 minutes to an hour, depending on the trajectory. The plus symbols indicate runs in which the pilot launched early. He followed the same nominal pitch program but at apogee oriented his vehicle, using the station's position as a cue, to thrust vertically in short bursts to maintain altitude, while taking advantage of his closing velocity to minimize the time for rendezvous. Early launches up to 1 minute early, can be made with little additional fuel usage. These studies have indicated that the pilot can bring his vehicle up to a relative range of 3 miles from which the final phase of rendezvous and docking would begin. Additional studies are required to determine fuel requirements for out-of-plane maneuvers.

Docking

The docking of two or more space vehicles has been the subject of many simulator studies. Presentation of the visual displays to the pilot have varied from simple light spots representing the vehicles (ref. 9) and closed-circuit television systems using models to complex facilities employing full-scale models of both the target vehicle and the spacecraft. (See reference 3 for several examples.) Figure 4 depicts a fixed-base docking simulator which employs closed circuit television to provide the visual display to the pilot. This simulator has been employed to study Gemini-Agena docking. A small-scale model of the target vehicle, having three angular degrees of freedom is mounted in front of the television camera. The model translates along the camera axis and rotates in response to commands from the pilot and analog computer. The image of the target is transmitted by the TV system to a 2-axis mirror above the Gemini pilot's head and is projected on the inside surface of a 20-foot-diameter spherical screen. Through the added action of the mirror system, all six degrees of freedom are simulated. The pilot and crewman are seated in a full-size wooden mockup of the Gemini spacecraft.

A photograph of the Langley rendezvous-docking facility is shown in figure 5. This moving-base simulator uses full-scale models of both the target vehicle and the Gemini spacecraft. The entire assembly is supported by a cable system attached to an overhead crane. The angular and linear motions are driven by servosystems through an analog computer. The target vehicle is suspended near the end of the track. This facility enables simulation of the docking maneuver from about 125 feet to actual contact. Six degrees of freedom are simulated and the system is driven in response to pilot control signals in accordance with the equations of motion which are solved by the analog computer. These facilities have been used to study piloting techniques, target lighting schemes, controls systems and malfunctions, and visual aids for docking.

The effects on docking of Gemini hand controllers and instruments and various initial conditions have been investigated with these facilities. Generally, it can be said that from an initial range of about 300 feet, with zero relative velocity between the spacecraft and the target vehicle a trained pilot can successfully complete docking in about 2 to 5 minutes using only visual information from the out-of-the-window display. Docking could be accomplished even under dark-side lighting conditions providing aids in the form of running lights were used on the target vehicle.

A group of seven NASA astronauts recently completed a study of Gemini-Agena docking using these facilities. Some of the results are shown in the next two figures. In figure 6 average longitudinal contact velocities are presented. These resulted from a total of 125 docking runs in both simulators with random initial conditions at an initial range of about 125 feet. All data were obtained without the use of instruments. None of the maximum velocities exceeded the tolerance of 1.5 fps. The average contact velocity of all astronauts in each simulator differed only by about 0.03 fps. Corresponding average lateral and vertical displacements (absolute values) are shown in figure 7. Although a few runs exceeded the tolerances, the difference in the average in each simulator was less than 2 inches. During this investigation it was found that after an average of about 10 runs in the moving-base simulator a pilot reached about the 90-percent proficiency level in meeting the tolerances at the point of contact. For the same number of runs in the fixed-base simulator the proficiency level was about 75 percent. This difference may result from the lack of motion cues or the lack of the three-dimensional effect near contact in the fixed-base simulator.

A short movie of a docking run in the moving-base simulator will be shown at this point in the talk.

Operational experience with devices of these types is very useful, not only in determining proper flight techniques, but for pointing out operational difficulties such as lighting requirements for various target lighting conditions and the evaluation of actual hardware to be used on space vehicles.

For example, the study with the seven astronauts and a previous study with six other astronauts have indicated that the Gemini phototype translation controller had some undesirable characteristics. Force levels were nonuniform in all three axes and because of looseness in the mechanism control inputs could not be applied as efficiently as desired. As a result of these studies, a redesign of the controller was undertaken. The general concensus of the astronauts was that these devices gave them valuable experience for determining techniques for approach and docking. They felt that the techniques developed would be employed on a space mission under conditions similar to those in the simulation.

Lunar Landing

One of the more critical tasks involved in lunar missions is that of performing the landing on the lunar surface. This phase is critical because of the stringent limitations placed on the touchdown velocity components, vehicle attitude, and fuel expenditure permitted in the task. Many simulator studies of lunar landings have been made. (See, for example, refs. 11 and 12.) One of these involved a six-degree-of-freedom study using a fixed-base all-instrument display (ref. 13). The pilot's task was to perform a soft landing in a designated area after deorbiting from a 50-mile circular orbit about the moon. Several techniques were employed in the landings, one of which is depicted in figure 8. When the pilot passed over a landmark, he initiated a thrust to deorbit, maintained the thrust for a preselected time, after which he increased the thrust by a factor of 3. This thrust was maintained until vehicle velocity components were reduced to almost zero and altitude decreased to a few thousand feet. The pilot then maneuvered to perform a soft landing. It was found that one pilot was extremely busy scanning instruments and flying. He had a tendency to hover for prolonged periods which used fuel rapidly, and he also tended to overshoot his landing site. When the task of landing was divided among two pilots, one controlling the throttle and the other attitude, the task of each was relatively easy and the prolonged periods of hovering were eliminated. Landings could be made within 2,000 feet of the landing site. Instrument resolution was the limiting factor in preciseness of landing point. The scanning problem which was mentioned for one-pilot flights was largely associated with the fact that vehicle attitude and direction of motion were presented to the pilot on numerous instruments. Much of the information could have been obtained from out-of-the-window displays of the lunarscape had they been available. The piloting task could then have been easier. More will be said on this topic when the planned facilities are discussed.

Man's Performance Under Lunar Gravity

Upon completion of the lunar landing the astronauts will debark from the Lunar Excursion Module (LEM) and move about the surface for exploration and make scientific measurements. Although there is little doubt that they will be able to walk, run, jump, carry loads, or perform other tasks under the condition of reduced gravity, there is very little information available to indicate how well they can perform these tasks (see ref. 14) what the proper suit design should be, or what auxiliary devices are required to aid them in performing the tasks. A technique has been developed at the Langley Research Center which makes it possible to study the performance of man under simulated lunar gravity conditions (ref. 15). The principles of the device are shown in figure 9. Any reduced gravity condition can be simulated by inclining the test subject relative to the vertical gravity vector. For the lunar gravity field, the subject is inclined 9.5° from the horizontal. The body is supported in this attitude by a number of cables located at the indicated points. Under normal conditions, the body members move primarily in parallel planes in performing most of the self-locomotion activities. This is also true for the test subject even though the body members are restricted by the cables. Figure 10 illustrates the general arrangement of the preliminary equipment that was developed. The test subject is supported by a series of small cables attached to a lightweight crossbar which, in turn, is attached to a trolley which is free to move along a monorail. A 16-foot-long, inclined walkway was located parallel to and about 40 feet below the monorail and represented the surface of the moon.

The performance of man under the conditions of the lunar gravity field are best illustrated by a movie which will be shown at this point in the talk.

AREAS OF PLANNED RESEARCH

The preceding discussion has given a brief indication of studies completed or nearly completed at the Langley Research Center. Next, an indication will be given of the studies which will be made in the near future and the facilities which are being developed for the studies. Emphasis will be directed toward the determination of the capability of man in the performance of various tasks involved in a space mission. This will be done to permit man to participate more actively in the mission, thereby achieving the maximum reliability of the man-machine system. It will be necessary to determine what types of aids may be useful to the astronauts. Also, it is necessary to determine the requirements for better, more efficient, display systems. This is especially true for situations in which time is critical where any long scan time for obtaining information may cause disastrous results. Studies will also be made to determine the ability of man to take advantage of his visual cues from his actual environment in case of failure of the instruments.

Two facilities are currently under construction at Langley which will be used to determine man's capabilities during lunar orbital flight, descent from lunar orbital flight, and lunar landing. Both simulators are designed to permit the pilots to obtain the maneuvering cues from out-of-the-window display.

Lunar Orbit and Letdown Approach Simulator

The Lunar Orbit and Letdown Approach Simulator (LOLA) is depicted in figure 11. This equipment consists of four models of the lunar surface, viewing systems to transmit views of the models to the display area, and a four-porthole display system. The four models were selected on the basis of a desired simulated altitude range of about 200 miles to 200 feet (322 km to 46 m) with a wide range of trajectories, a minimum distance of viewing optics to the models of 3/4 inch, and a practical size for construction and housing in an existing structure. Scale factors for each model may be found in the printed text of this paper.

The scale factors, altitude, and surface range of each map are as follows:

Model	Scale factor, km/in.	Surface range, km	Altitude range, km
Sphere	14.5	Complete orbits	11.3 to 322
Map 1	3.2	1,545	2.4 to 11.3
Map 2	0.8	319	0.6 to 2.4
Map 3	61 meters/in.	26 km	46 m to 0.6 km

The region around Crater Alphonsus was selected as the landing site for simulation studies because of the scientific interest and because regions of the most rugged mountains on the moon lie on the approach. Therefore, it presents the pilot with an exacting navigational task. Orbital inclinations up to 15° can be simulated with the spherical model. The surface of the spherical model will be flat with the lunarscape painted on plastic gores which are then mounted on the surface. All other models are relief maps with shadow patterns painted on to give the proper appearance. All models are internally or back lighted.

The models are viewed by two TV camera clusters mounted on transport mechanisms. The transport mechanisms have three translational degrees of freedom and the gimballed camera cluster provides three angular degrees of freedom so that six-degree-of-freedom motion can be simulated. One group of four TV cameras, in each of two clusters of cameras, furnishes the display information to the pilot. The simulated vehicle will have four portholes, a TV camera providing each with a 65° simulated field of view. The portholes will have a 45° field of view to enable the pilot some freedom to move his head without seeing the edge of the display.

Pilot control signals are transmitted to the computer which, in turn, drives the TV camera transport and gimbal mechanisms so that the pilot in effect flies the camera over the lunar surface. During a descent, the system viewing the spherical model of the moon will furnish display information to the pilot until the lower limit of travel is reached. Before this lower limit is reached the second camera cluster is automatically switched on for map 1. Similar switching will be made through the remainder of the descent.

In order to use the sphere and map 1 before the TV system is operational, a 180° motion-picture camera-projector has been developed. Preprogramed trajectories will be filmed. The motion pictures will then be projected within the sphere giving a 180° field of view. The pilot will be an observer and will not have control over the display. This presentation will be used to test man's ability to perform observational tasks which would precede any control action and to determine his orbital ephemeris.

LOLA should define those control tasks best performed by man or machine and thus will determine the most effective man-machine integration for the lunar mission. Studies with the preprogramed trajectories should begin in June 1964, and the complete system should be in operation in the second quarter of 1965.

LUNAR LANDING RESEARCH FACILITY

Because gravity on the moon is only 1/6 that of the earth, thrust levels for lunar operations are very low compared with those required for VTOL flight on earth. In order to produce reasonable horizontal accelerations for braking and maneuvering during lunar landing, large attitude angles (up to 30° or more) will be required, and this may pose serious visibility and attitude and thrust-control problems. A facility designed to study the piloting problems of the final phase of a lunar landing is presently under construction at the Langley Research Center. Simulation with this facility begins at about the altitude where LOLA stops.

An overall layout of the facility is shown in the next figure (fig. 12). The gantry supports a traveling crane from which the vehicle is suspended. The crane system supports 5/6 of the weight of the vehicle through servocontrolled vertical cables, while the remaining 1/6 of the weight pulls downward and simulates the lunar gravitational force. The overhead crane is slaved to move with the vehicle linear motions to keep the cables vertical. A gimbal system on the vehicle permits angular freedom in pitch, roll, and yaw.

Vehicles weighing up to 20,000 pounds, and as large as the full-scale lunar excursion module used in the Apollo Project, can be tested on this facility. The pilot can maneuver in complete six degrees of freedom in a volume 400 feet long, 165 feet high, and 50 feet wide. Through the use of a catapult, initial velocities up to 50 fps horizontally and 40 fps vertically can be provided.

A photograph of the test vehicle is shown in figure 13. The vehicle gross weight is 10,000 pounds including a two-man crew and 3,300 pounds of fuel. Fuel is 90-percent hydrogen peroxide. The main motors provide 6,000 pounds of thrust with a 10-to-1 throttling range. Attitude motor thrust is ground adjustable to produce angular accelerations from 0.1 to 0.5 rad/sec^2 about all axes. The fuel load will permit about 3 minutes of operation.

The pilot's bubble can be masked to determine the effect of the viewing area on his ability to land safely. It is anticipated that requirements for instrument displays will be developed as the simulation program proceeds. The establishment of requirements for performing a lunar landing will be accomplished by measuring pilot performance. Piloting techniques, visibility, and abort modes will be major items of study using this simulator. Construction of this facility was started in January 1962, and is now nearing completion. Research studies will start in the spring of 1964.

CONCLUDING REMARKS

In conclusion, the Langley Research Center has been examining, through analytical and simulation studies, techniques for pilot control of various tasks of space missions. Simplified techniques and pilot utilization should increase the reliability of space missions. Results of simulator studies conducted thus far have shown that, given proper information, pilots can perform rendezvous, docking, lunar landing, and launch from the lunar surface. Although none of these missions have actually been performed in space the usefulness of simulator devices has been demonstrated in Project Mercury. Sixteen different types of simulators were used during the preparation for flight, with eight devices found to be essential and only three had questionable value (ref. 16). Two places where the simulations were found to be inadequate were in the period of transition to a weightless state after orbital insertion and the view of the earth through the spacecraft window. Weightlessness could not be simulated for more than about a minute and, until late in the program, an out-of-the-window display was not available in a simulation device. As an example of the usefulness of simulation devices, during the MA-8 flight, the astronaut was able to perform a turnaround maneuver in space in an identical manner as it had been practiced on the procedures trainer.

Simulation devices such as LOLA and the Lunar Landing Research Facility will provide information necessary to perform lunar and other space missions.

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A. EARTH LAUNCH
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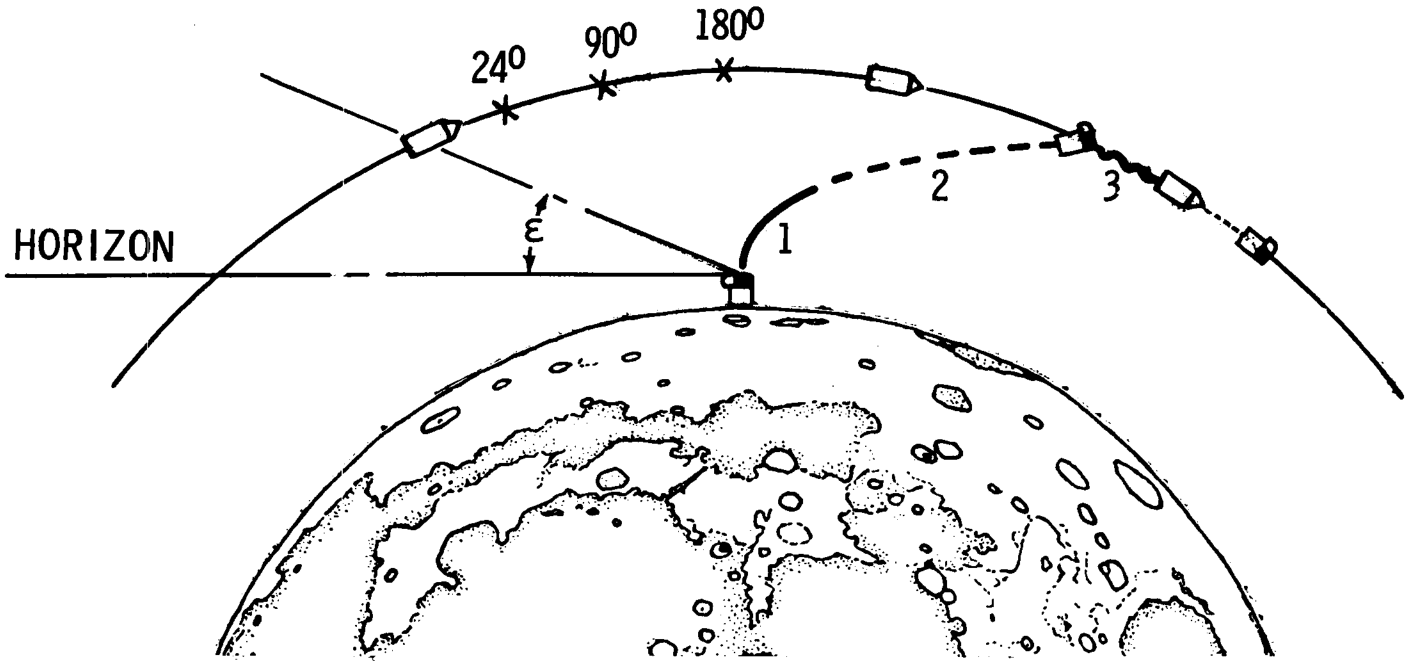
D. DOCKING
E. LUNAR ORBIT ESTABLISHMENT
F. LUNAR LANDING
G. LUNAR LOCOMOTION AND WALKING
H. LUNAR LAUNCH
I. ENTRY AND EARTH LANDING

NASA

Figure 1.- Task areas of simulation studies.



1. BOOST PHASE
2. COAST PHASE
3. RENDEZVOUS PHASE

NASA

Figure 2.- Lunar take-off and rendezvous trajectory.

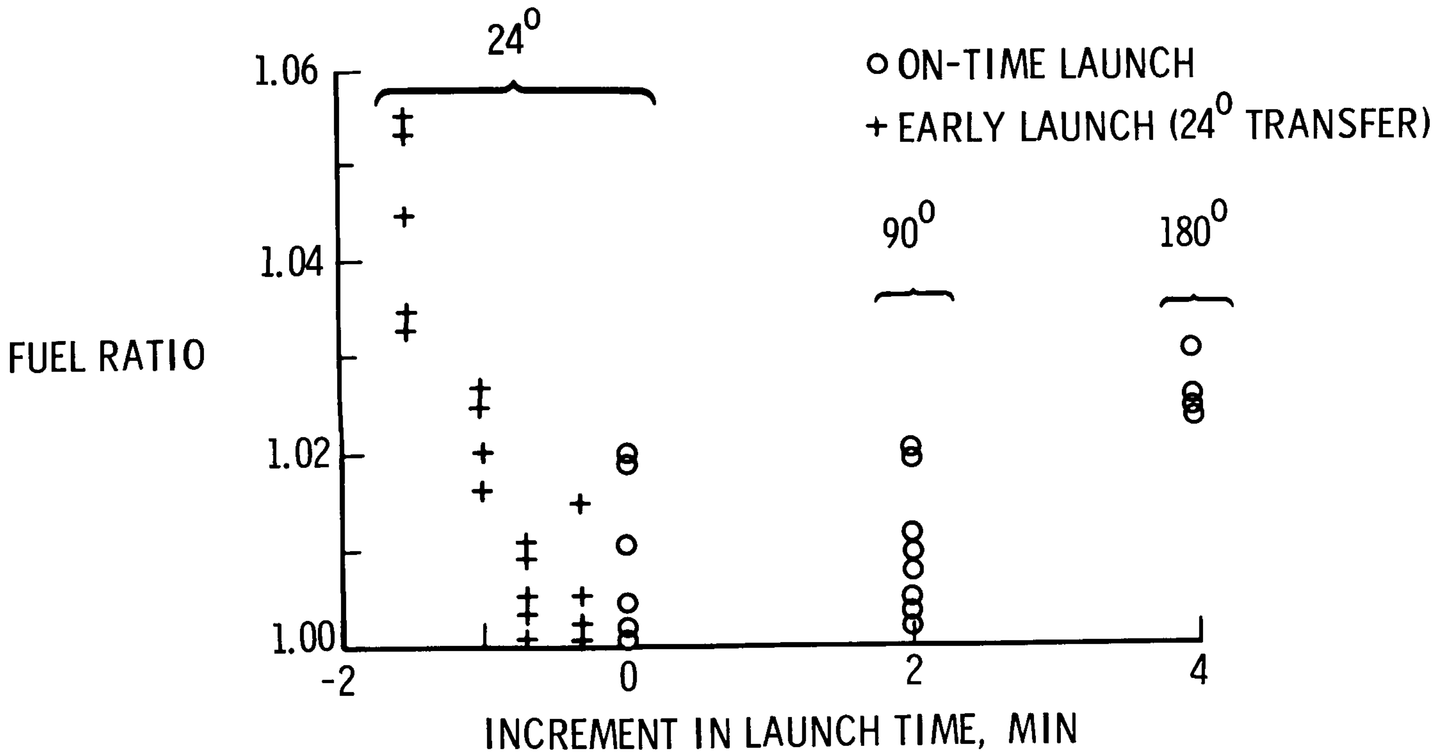


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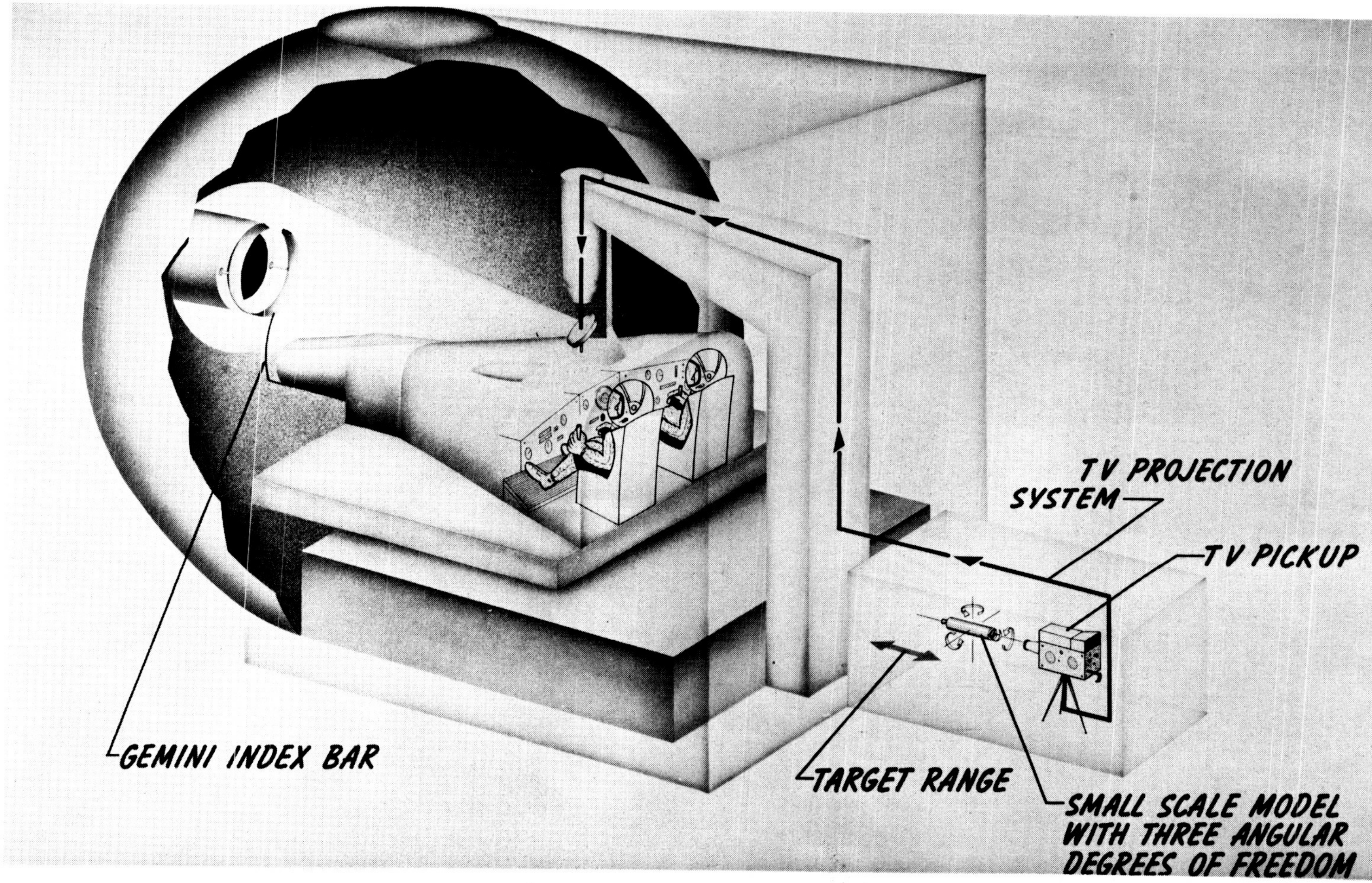
Figure 3.- Fuel ratio plotted against increment in launch time.



NASA

Figure 4.- Visual docking simulator.

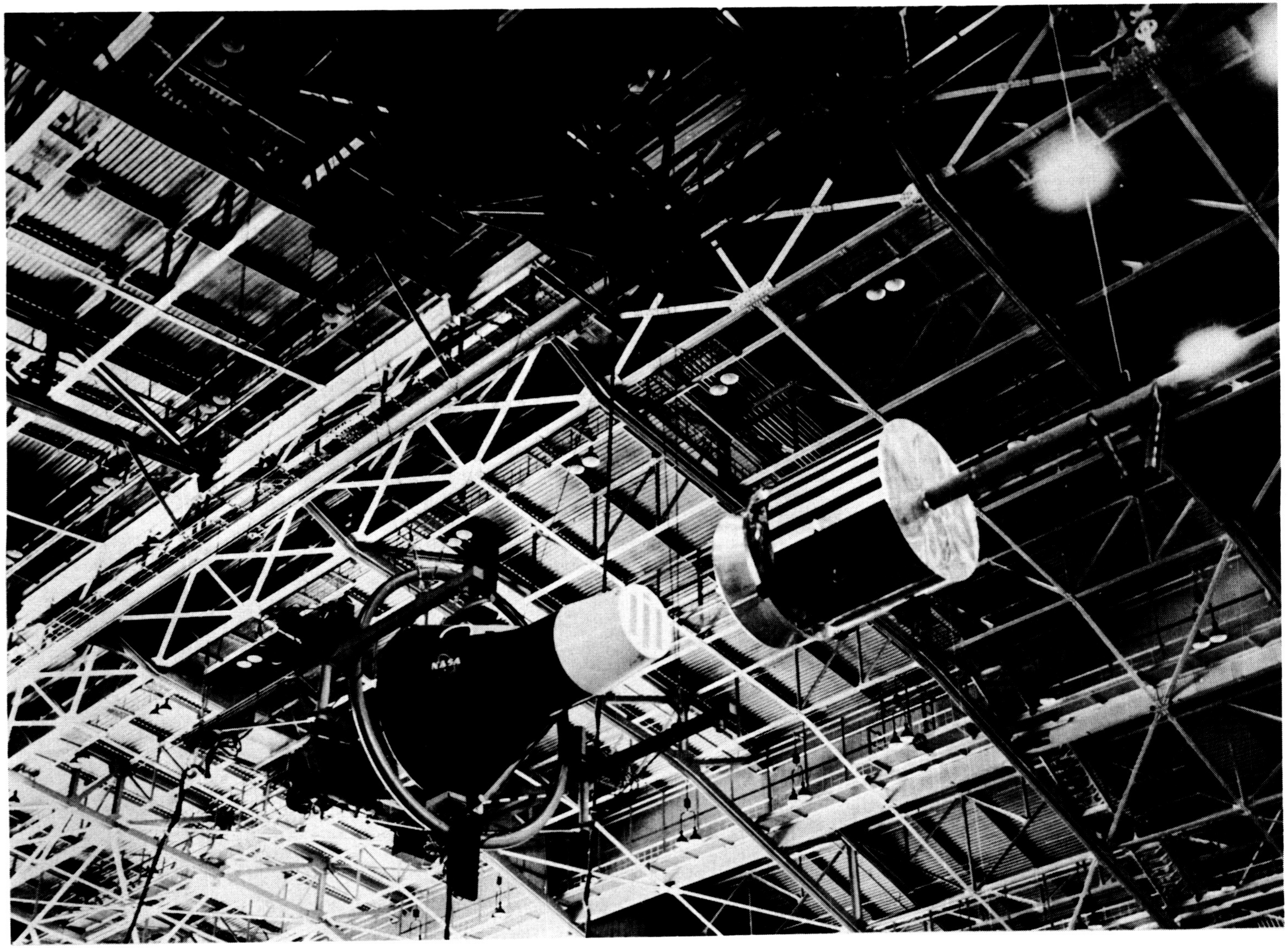


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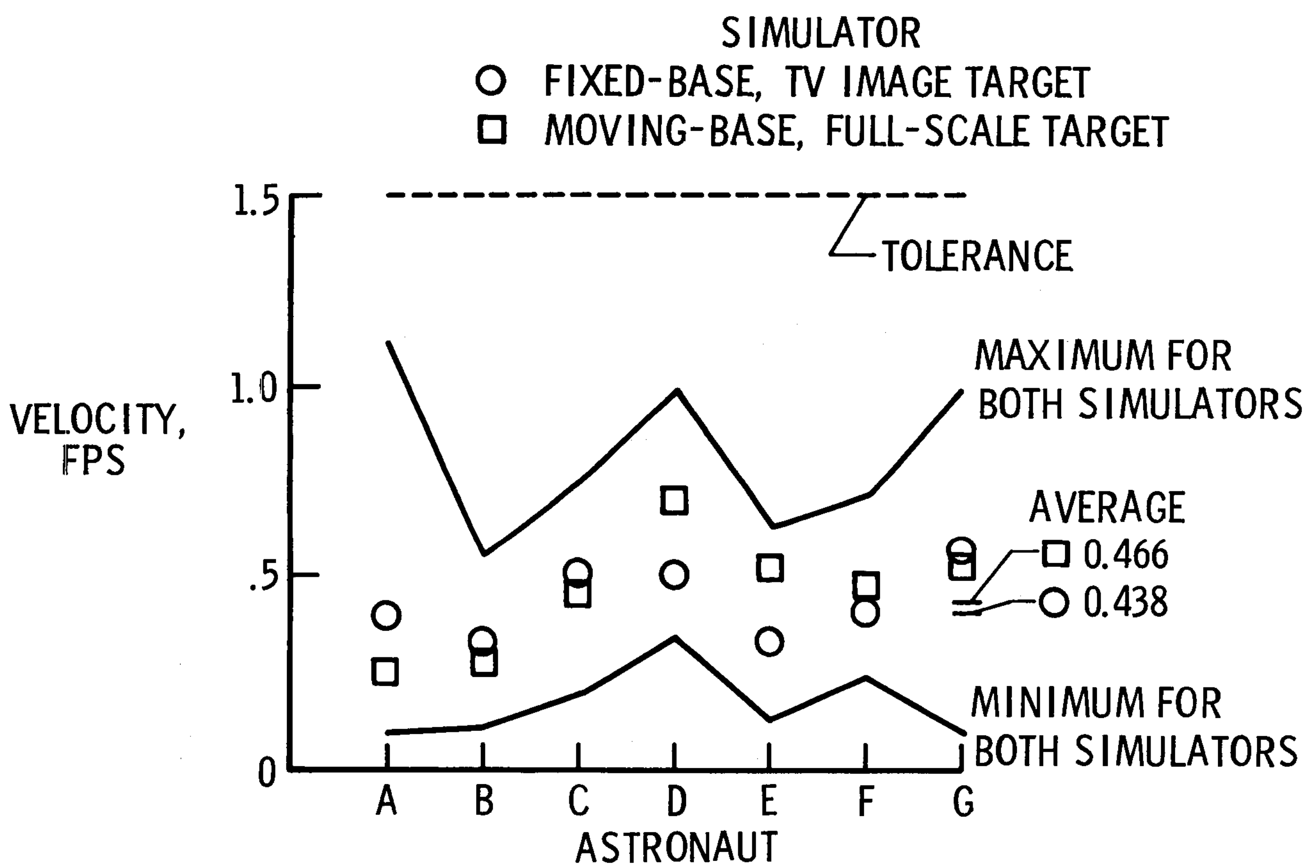
Figure 5.- Rendezvous docking simulator.



NASA

Figure 6.- Average longitudinal contact velocities for 125 docking runs from 125-foot initial range using out-of-window display.

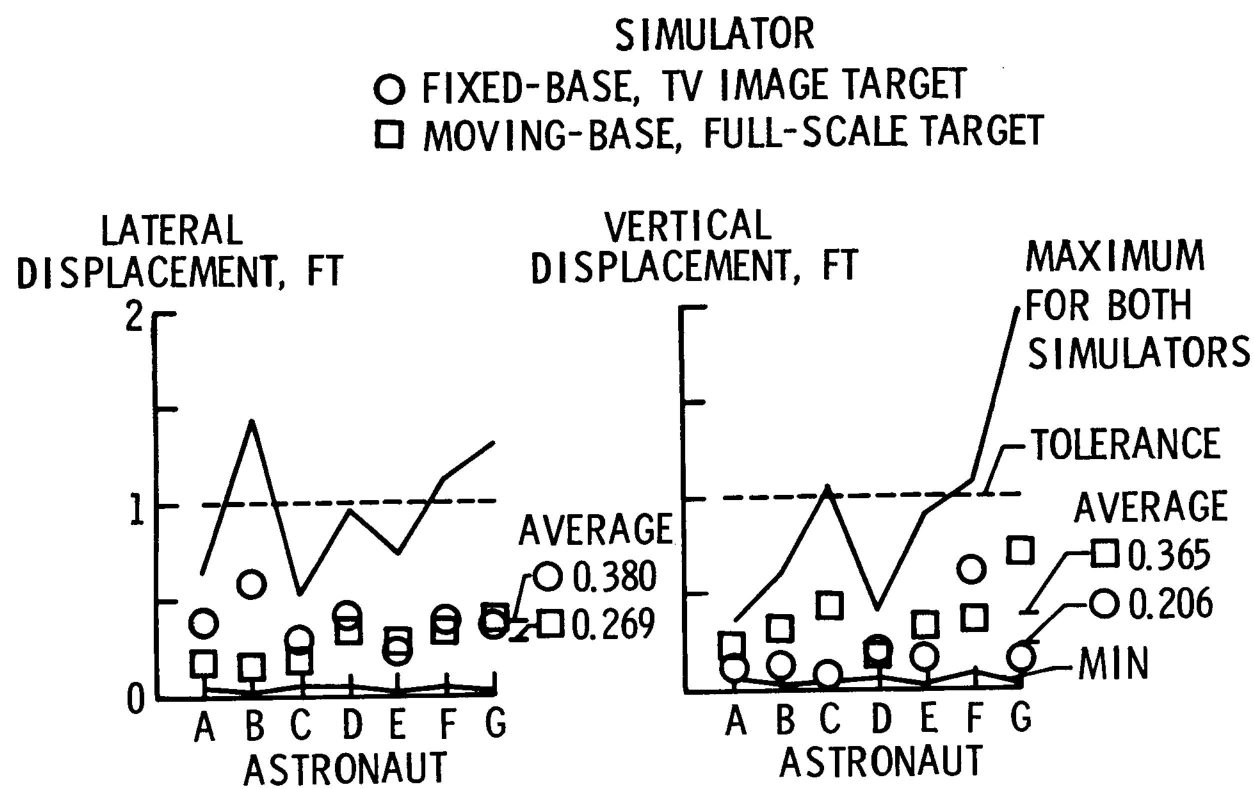


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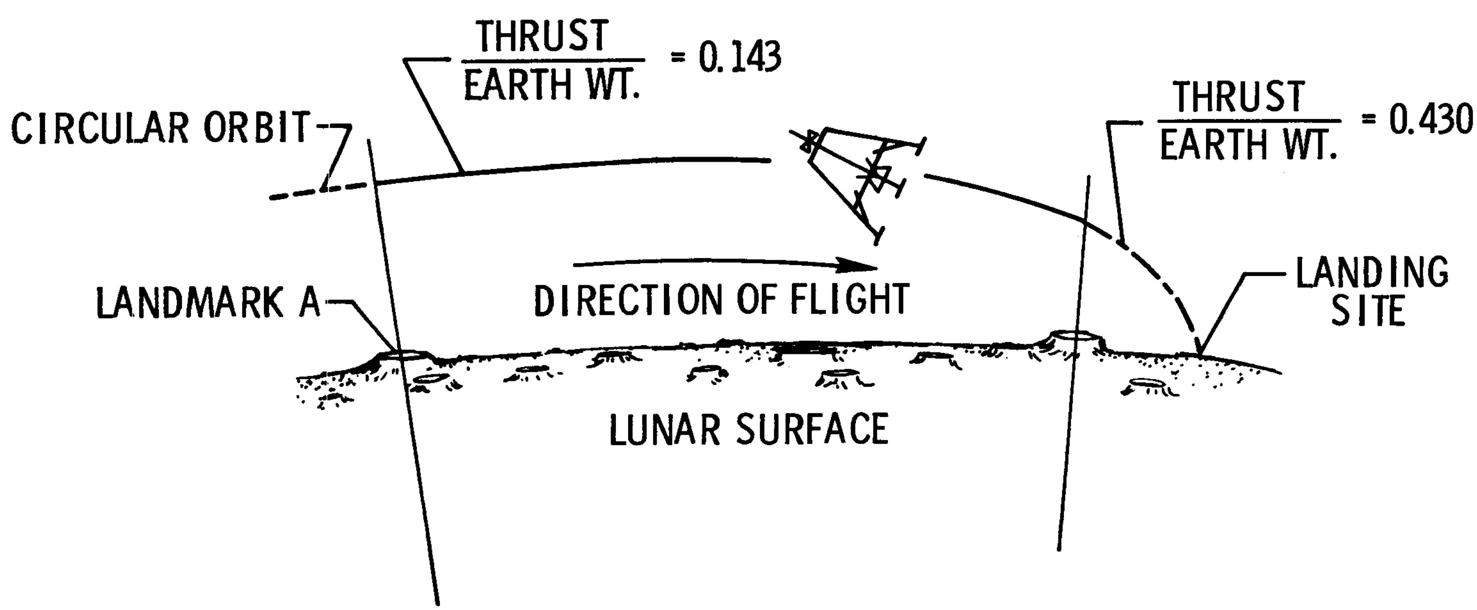
Figure 7.- Absolute average values of lateral and vertical displacements at contact, 125 runs.



NASA

Figure 8.- Nominal gravity-turn lunar landing trajectory.

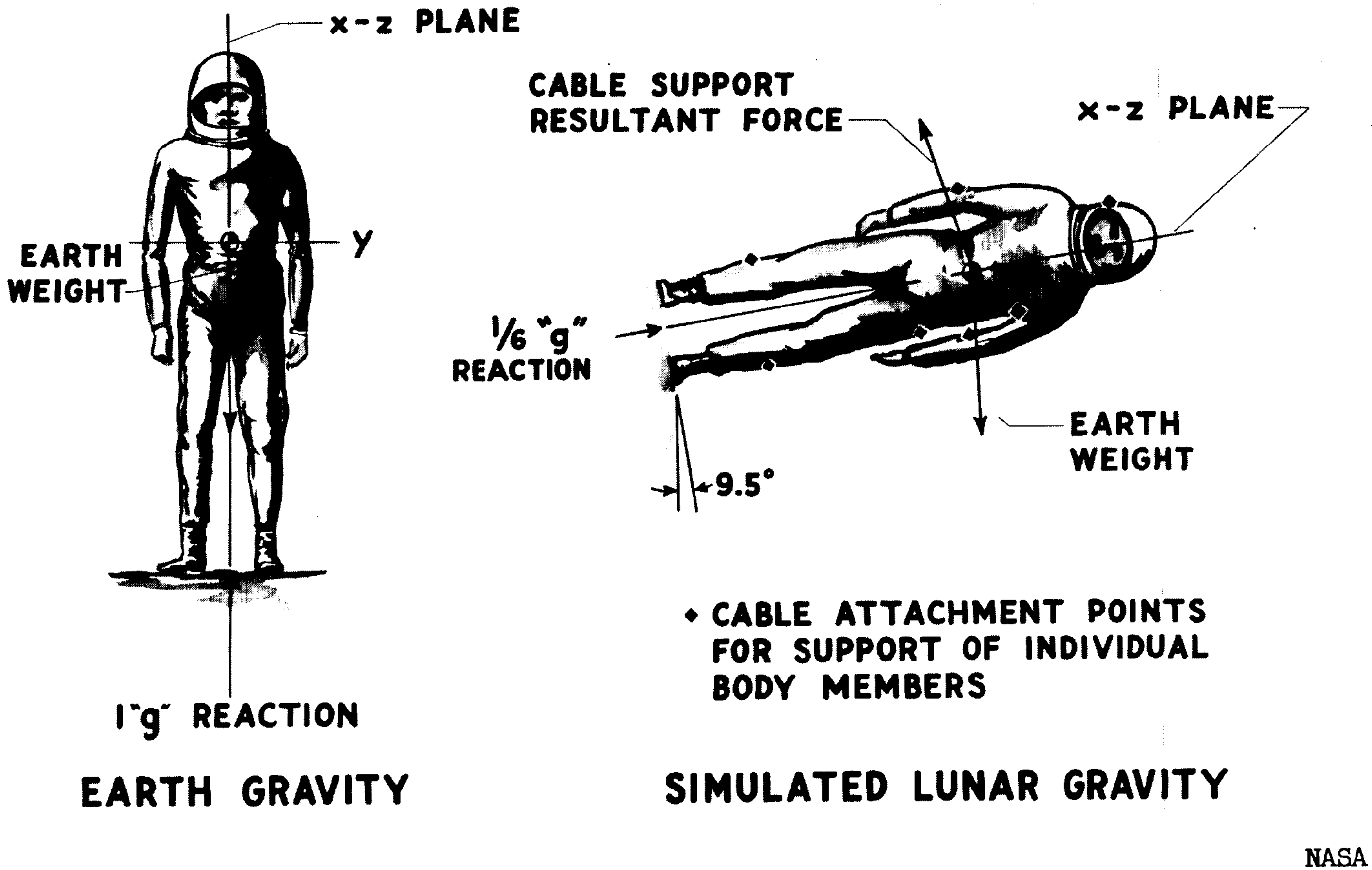
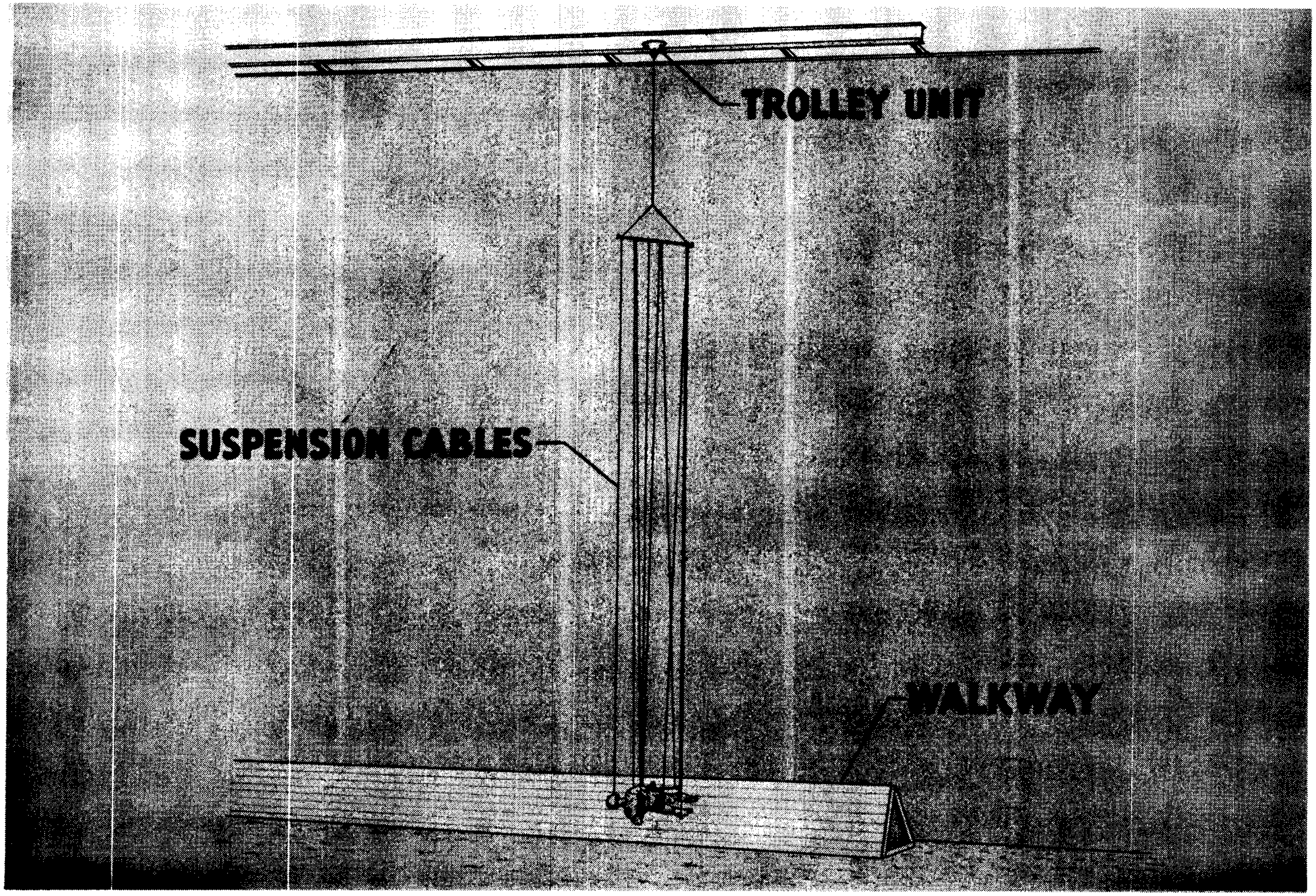
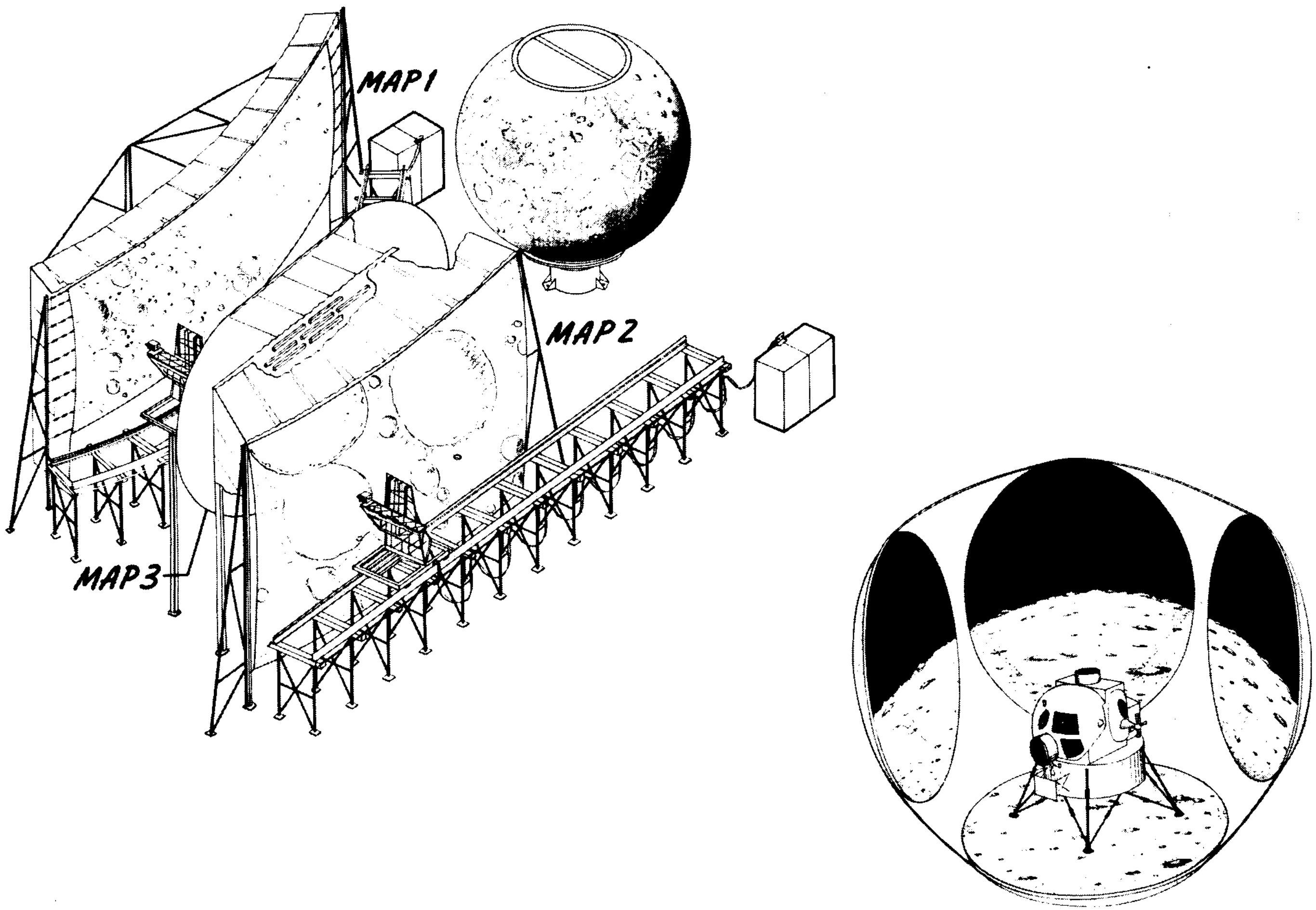


Figure 9.- Lunar gravity simulation.



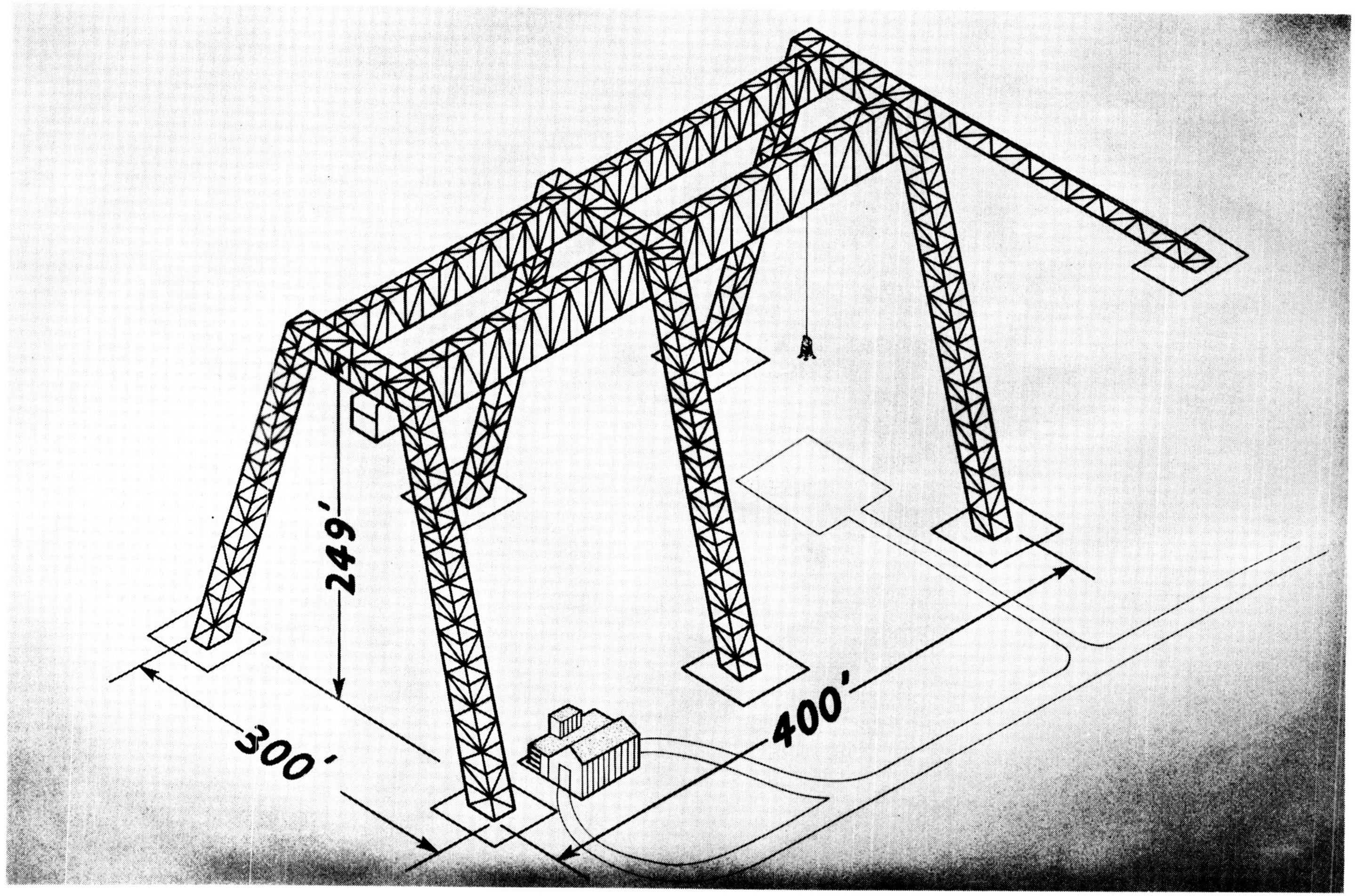
NASA

Figure 10.- Langley lunar gravity simulator.



NASA

Figure 11.- Lunar let-down simulator.



NASA

Figure 12.- Lunar landing research facility.

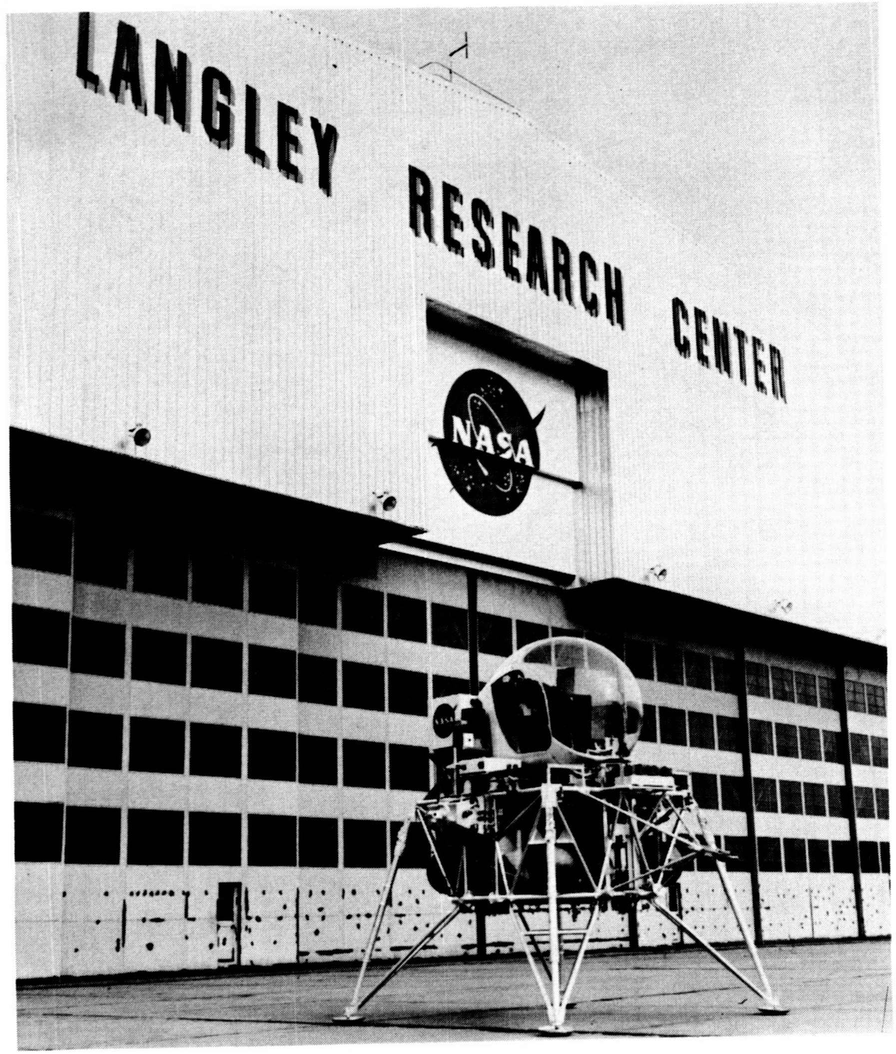


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Figure 13.- General research vehicle for lunar landing research facility.

NASA-Langley, 1964